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RESEARCH MEMORANDUM

PRELIMINARY TESTS IN THE SUPERSONIC SPHERE

By

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

This report presents preliminary data obtained in the Langley supersonic sphere. The supersonic sphere is essentially a whirling mechanism enclosed in a steel shell which can be filled with either air or Freon gas. The test models for two-dimensional study are of propeller form having the same plan form and diameter but varying only in the airfoil shape and thickness ratio. Torque coefficients for the 16-006, 65-110, and the 15-percent-thick ellipse models are presented, as well as pressure distributions on a circular-arc supersonic airfoil section having a maximum thickness of 10 percent chord at the $\frac{1}{3}$-chord position.

Torque coefficients were measured in both Freon and air on the 15-percent-thick ellipse, and the data obtained in air and Freon are found to be in close agreement.

The torque coefficients for the three previously mentioned models showed large differences in magnitude at tip Mach numbers above 1, the model with the thickest airfoil section having the largest torque coefficient.

Pressure distributions on the previously mentioned circular-arc airfoil section are presented at Mach numbers of 0.69, 1.26, and 1.42.

At Mach numbers of 1.26 and 1.42 the test section is in the mixed flow region where both subsonic and supersonic speeds occur on the airfoil. No adequate theory has been developed for this condition of mixed flow, but the experimental data have been compared with values of pressure based on Ackeret's theory.

The experimental data obtained at a Mach number of 1.26 on the rear portion of the airfoil section agree fairly well with the values calculated by Ackeret's theory. At a Mach number of 1.42 a larger percentage of the airfoil is in supersonic flow, and the experimental data for the entire airfoil agree fairly well with the values obtained using Ackeret's theory.

INTRODUCTION

Research on disks and streamlined rods rotating in Freon (reference 1) demonstrated the feasibility of larger scale testing in this gas. The initial research program for the study of airfoil characteristics in Freon was assigned to the supersonic sphere, since the power requirements and instrumentation costs would be much less than for a sufficiently large supersonic wind tunnel. The supersonic sphere is essentially a whirling mechanism enclosed in a steel shell that can be sealed from the atmosphere and filled with either air or Freon gas.

The investigations in the supersonic sphere under the present program include pressure distributions, and torque and thrust measurements at transonic and supersonic speeds for models of conventional airfoil shapes as well as sharp-edge supersonic airfoils

The models for two-dimensional study are built in propeller form with the desired airfoil shapes. This method of study yeilds approximately two-dimensional results which are sufficient for the comparative results required in the present research program.

This report presents preliminary data which has been obtained from the supersonic sphere tests. Included in this presentation are torque measurements on the 16-006, 65-110, and the 15-percent-thick ellipse models as well as pressure distributions on a circular-arc airfoil having a maximum thickness of 10 percent chord at the $\frac{1}{3}$-chord position.

APPARATUS AND TEST METHODS

The supersonic sphere is essentially a whirling mechanism enclosed in a steel shell which can be sealed from the atmosphere and filled with either air or Freon-12 gas at pressures necessary for the desired testing conditions. The whirling mechanism is driven by a 500-horsepower variable-frequency motor. (See figs. 1 and 2.) The preliminary tests in the supersonic sphere were made without the use of the stationary spinner shown in figure 2. Additional necessary equipment installed in the supersonic sphere include torque and thrust measuring devices, a sound speed meter that supplies the sound speed of the fluid in the sphere, a thermometer for measuring the sphere temperature, and a refrigeration installation which keeps the sphere temperature below the maximum safe operating limit.

The cooling fan in the refrigeration apparatus circulates the fluid around the sphere, shown schematically in figure 1, at a maximum velocity of approximately 20 miles per hour through the plane of rotation of the model. This small velocity as compared with the large velocity of the rotating model has a small effect on the effective angle of attack, but the torque coefficients are not sensitive to small changes of the angle of attack when the model is at 0° pitch.

The sphere can be filled with Freon gas having a sound velocity of approximately 320 miles per hour (table I). Since a tip speed of 960 miles per hour can be attained on the whirling arm, a Mach number of 3 can be reached.

The two-dimensional test models are built in propeller form with the desired airfoil section. (See figs. 2 and 3.) Flutter and vibration data are supplied by strain gages on the models and vibration pickups on the motor and supporting struts, the purpose being to indicate when excessive flutter and vibration occur so that these conditions may be avoided in the interests of safety.

Torque and thrust measurements are made on these models, supplying data from which the comparative lift and drag coefficients of the models may be calculated.

Pressure distributions are also taken along the chord of a section of the model located slightly over ¼-chord length from the tip. The pressure tubes from the test section are inlaid along the span of the model and transmit the pressures to the axis of rotation. A rotating multichannel pressure seal then transmits the pressures from the rotating model to the pressure tubes leading to the mercury multimanometer mounted in the laboratory test panel (fig. 4).

A section view of the 10-channel rotating pressure seal used in the supersonic sphere is shown in figure 5. The outer shell and the small inner tube are attached to the hub of the whirling model and rotate with it. Ten 0.050-inch pressure tubes are connected externally to the pressure tubes on the model and extend into the small inner tube where they terminate at $\frac{5}{8}$-inch intervals flush with the outside of this tube. The stationary portion of the transmitter is supported by the rotating outer shell and holds 10 discs spaced so that they cover each of the points on the small inner tube where the rotating pressure tubes terminate. A channel machined on the inside of the center hole in each disk provides a chamber for transmitting the pressures from the rotating tube to the stationary part of the assembly. The channels are sealed against pressure

leakage by short lengths of neoprene tubing on both sides of each disk, and held in place by filling the surrounding chamber with glycerin under pressure. Two 0.050-inch tubes are vented from the channel in each disk, the upper tube leading to the manometer in the laboratory, and the lower tube functioning as a drain to relieve the pressure system of any glycerin that leaks in from the glycerin seal.

Torque measurements have been made in both air and Freon on models having approximately the same plan form and diameter and varying only in airfoil shape and thickness ratio (fig. 3 and table II). The same hub was used for each model, this enabling a direct comparison of the data obtained. Preliminary torque measurements have been made at 0° pitch on models having the airfoil shapes, 16-006, 65-110, and 15-percent-thick ellipse (fig. 6).

Preliminary pressure distributions have also been made in Freon gas on a model having a circular-arc airfoil section with a maximum thickness of 10 percent chord at the $\frac{1}{3}$-chord position. (fig. 6). This is a supersonic airfoil having a sharp leading and trailing edge built into a model having a rectangular plan form and a tapered thickness ratio along the radius (table II). The model was mounted in a special slotted hub which was designed for this purpose.

RESULTS AND DISCUSSION

The torque data observed for the 16-006 model, the 65-110 model, and the 15-percent-thick ellipse model are shown in figure 7 as a function of the tip Mach number. The probable torque due to the hub drag is also shown, and the torque coefficients shown for the three models have not been corrected for this factor. The torque data have been reduced to the coefficients by the general formulas,

$$C_Q = \frac{Q}{\rho n^2 D^5}$$

where

Q torque, pound feet

ρ mass density, slugs per cubic foot

n rotational speed, revolutions per second

D tip diameter of the model, feet

Experimental data obtained in full atmosphere air and $\frac{1}{4}$-atmosphere Freon on the 15-percent-thick ellipse model have been compared and the results presented in figure 7. The Reynolds numbers for this model, calculated for a 5-inch chord and a Mach number of 1, are approximately 3,000,000 for full atmosphere air and 2,000,000 for $\frac{1}{4}$-atmosphere Freon. Additional data not presented in this report indicate that the torque coefficients for this model are not sensitive to the Reynolds number effect in this range of Reynolds number. The good agreement between the air and Freon data as seen in figure 7 indicates that there is no appreciable discrepancy between data obtained in Freon and air.

An appreciable difference can be seen in the magnitude of the torque coefficients obtained for the three models tested. This variation is probably due primarily to the thickness effect. The torque due to the hub drag tends to flatten out the C_Q curves after the maximum values are reached because of the rapid increase in the hub drag at high tip Mach numbers. This increase is caused by the increase in hub drag when the local velocities on the hub exceed a Mach number of 1. The installation of a spinner is expected to decrease this effect.

Three pressure distributions obtained on a circular-arc supersonic airfoil section having a maximum thickness of 10 percent chord at $\frac{1}{3}$ chord operating in Freon gas are presented in figure 8. The pressure coefficients $\frac{\Delta p}{q}$ are plotted as a function of the chord, where Δp is the difference between the pressure on the airfoil and the stream pressure, and q is the dynamic pressure $\frac{1}{2}\rho V^2$. The pressures shown have been corrected for centrifugal force and temperature variation along the span of the model. The derivation for the pressure correction is given in the appendix.

The experimental data taken at a Mach number of 0.69, shown in figure 8(a), correspond fairly well with the theoretical compressible curve. It is difficult to draw any conclusions at this Mach number since the three-dimensional effect of the tip of the model may cause a deviation from the assumed two-dimensional flow.

Supersonic flow over the entire airfoil has not been attained at Mach numbers of 1.26 and 1.42, the experimental data being shown in figure 8(b) and 8(c). A stream Mach number of 1.58 must be

reached before total supersonic flow is obtained, due to the magnitude of the turning angle at the leading edge of the airfoil section. No adequate theory has been developed for the condition of mixed flow at supersonic speeds, but the curves based on Ackeret's theory are shown, the pressure coefficients given by Ackeret's thin airfoil theory (reference 2):

$$\frac{\Delta p}{q} = \frac{2\epsilon}{\sqrt{M^2 - 1}}$$

where

ϵ slope of the surface to the direction of flow, radians

M stream Mach number

It is interesting to note in figure 8(b) that at a Mach number of 1.26 the experimental data on the rear surface of the airfoil correspond very closely to the curve based on Ackeret's theory. At a Mach number of 1.42 more of the airfoil is in supersonic flow, and from figure 8(c) it can be observed that the experimental data on both the leading and trailing surface of the airfoil correspond fairly well with Ackeret's curve.

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APPENDIX

The pressures recorded from the manometer are not the pressures occurring at the test section but are those found at the center of rotation. A correction must be made for the centrifugal force on the column of gas in the pressure tubes located along the model. The fundamental equation for the centrifugal force is

$$dp = \rho\omega^2 r\, dr \tag{1}$$

From the perfect gas law, $\rho = \frac{Kp}{T}$

Substituting this equivalent in equation (1) gives

$$\frac{dp}{p} = \frac{K\omega^2 r\, dr}{T} \tag{2}$$

Since the temperature along the radius of the model is not constant, the following correction for temperature was used in analyzing this preliminary data.

The adiabatic relationship for the stagnation temperature is given by

$$\frac{T_s}{T_o} = 1 + \left(\frac{\gamma - 1}{2}\right) M^2 \tag{3}$$

where

T_s stagnation temperature

T_o stream temperature

γ ratio of specific heats $\left(\frac{c_p}{c_v}\right)$

M stream Mach number

It has been found that the temperature in the boundary layer is approximately 0.8, the correction for the stagnation temperature, transforming equation (3) to

$$\frac{T_B}{T_o} = 1 + 0.4\ (\gamma - 1)\ M^2 \tag{4}$$

where

T_B temperature in the boundary layer

Substituting the value of T_B from equation (4) into equation (2) and carrying out the integration, results in the following correction for pressures:

$$\frac{P_t}{P_c} = e^{\left\{\frac{\gamma}{0.8(\gamma-1)}\ \ln\left[1+0.4\left(\gamma-1\right)\ M_t{}^2\right]\right\}} \tag{5}$$

which reduces to

$$\frac{P_t}{P_c} = \left[1 + 0.4(\gamma - 1)M_t{}^2\right]^{\left[\frac{\gamma}{0.8(\gamma-1)}\right]} \tag{6}$$

where

M_t the stream Mach number of the test section

P_t the pressure at the test section

P_c the pressure at the center of rotation

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1. Theodorsen, Theodore and Regier, Arthur A.: Experiments on Drag of Revolving Disks, Cylinders, and Streamline Rods at High Speeds. NACA ACR No. L4F16, 1944.

2. Taylor, G. I. and Maccoll, J. W.: The Mechanics of Compressible Fluids. Vol. III of Aerodynamic Theory Two-Dimensional Flow at Supersonic Speeds. div. H, ch. IV, sec. 1, W. F. Durand, ed., Julius Springer (Berlin), 1935, pp. 234 - 236.

3. Huber, Paul W.: Use of Freon-12 as a Fluid for Aerodynamic Testing. NACA TN No. 1024, 1946.

TABLE I

THERMODYNAMIC CHARACTERISTICS OF FREON-12 GAS

AND AIR AT 32° F AND 1 ATMOSPHERE PRESSURE[a]

	Sound velocity (ft/sec)	Density (slugs/ft^3)	Viscosity μ (slug/ft sec)	Maximum Reynolds number[b]	Specific heat c_v (Btu/lb°R)	γ $\frac{c_p}{c_v}$
Freon-12	472	0.01061	2.44×10^{-7}	21.4×10^6	0.1178	1.14
Air	1089	.002508	3.61×10^{-7}	3.42×10^6	.1713	1.40

[a]Reference 3.

[b]The Reynolds number is calculated at 83.4 percent of the radius, where the chord is 5 in., for a velocity of 1180 fps corresponding to the maximum speed at which these models were run (4500 rpm).

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TABLE II

DIMENSIONS OF THE TEST MODELS

[All models except the circular-arc model have a radius of 36.125 inches and a straight chord taper beyond the radius of the maximum chord. The tips are rounded as seen in figure 3]

Airfoil section	At 47.4 percent radius			At 83.4 percent radius		
	Chord (in.)	Thickness (in.)	Thickness (percent chord)	Chord (in.)	Thickness (in.)	Thickness (percent chord)
15-percent ellipse	7.31	1.096	15.0	5.0	0.750	15.0
65-110	7.00	.700	10.0	5.0	.500	10.0
16-006	7.00	.420	6.0	5.0	.300	6.0
Circular arc (maximum thickness at 1/3 chord)	5.00	1.000	20.0	5.0	.500	10.0

The effective hub causing the torque due to hub drag shown in figure 7 extends to a 15-inch radius.

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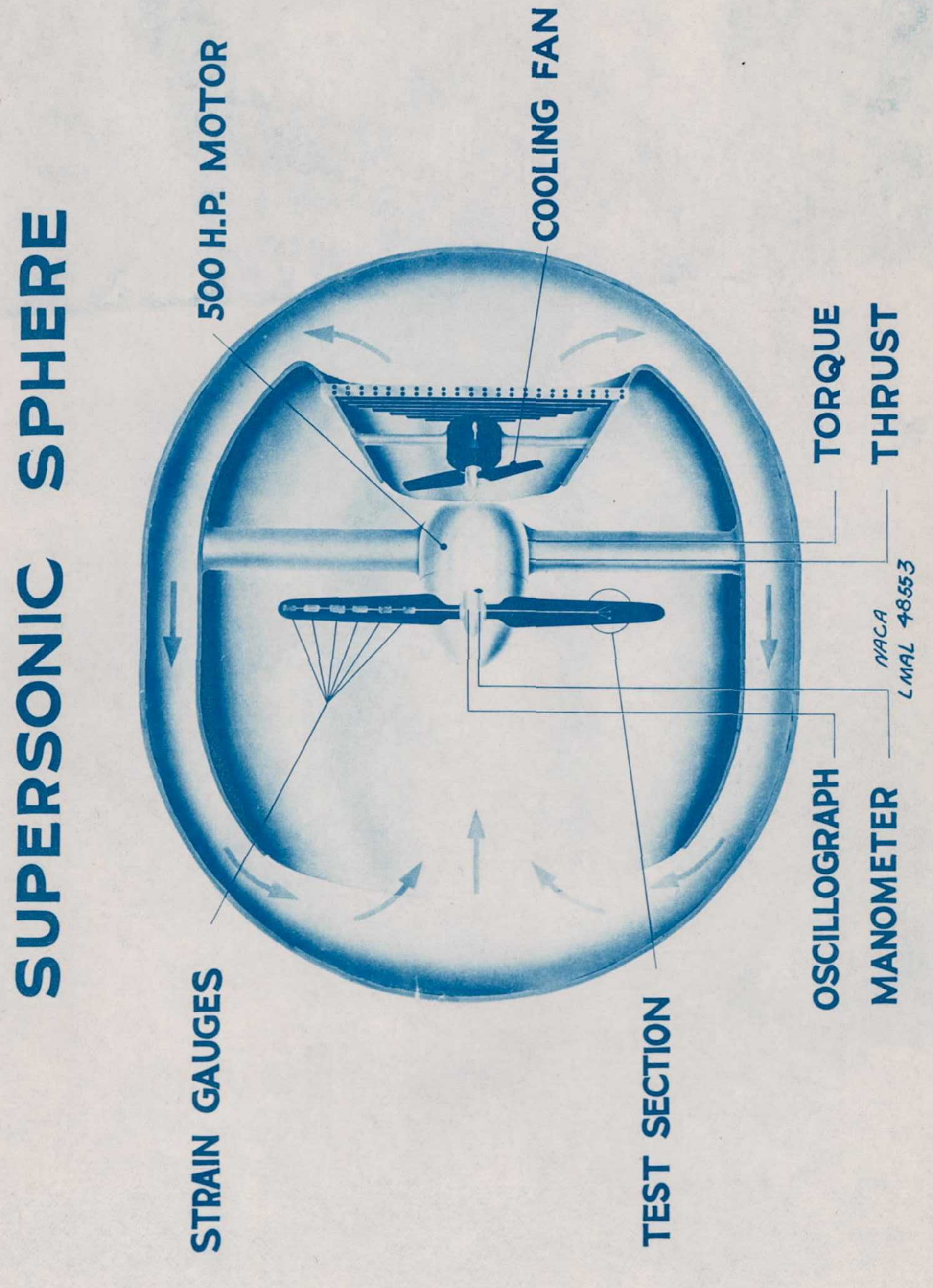

Figure 1.- Schematic diagram of the supersonic sphere.

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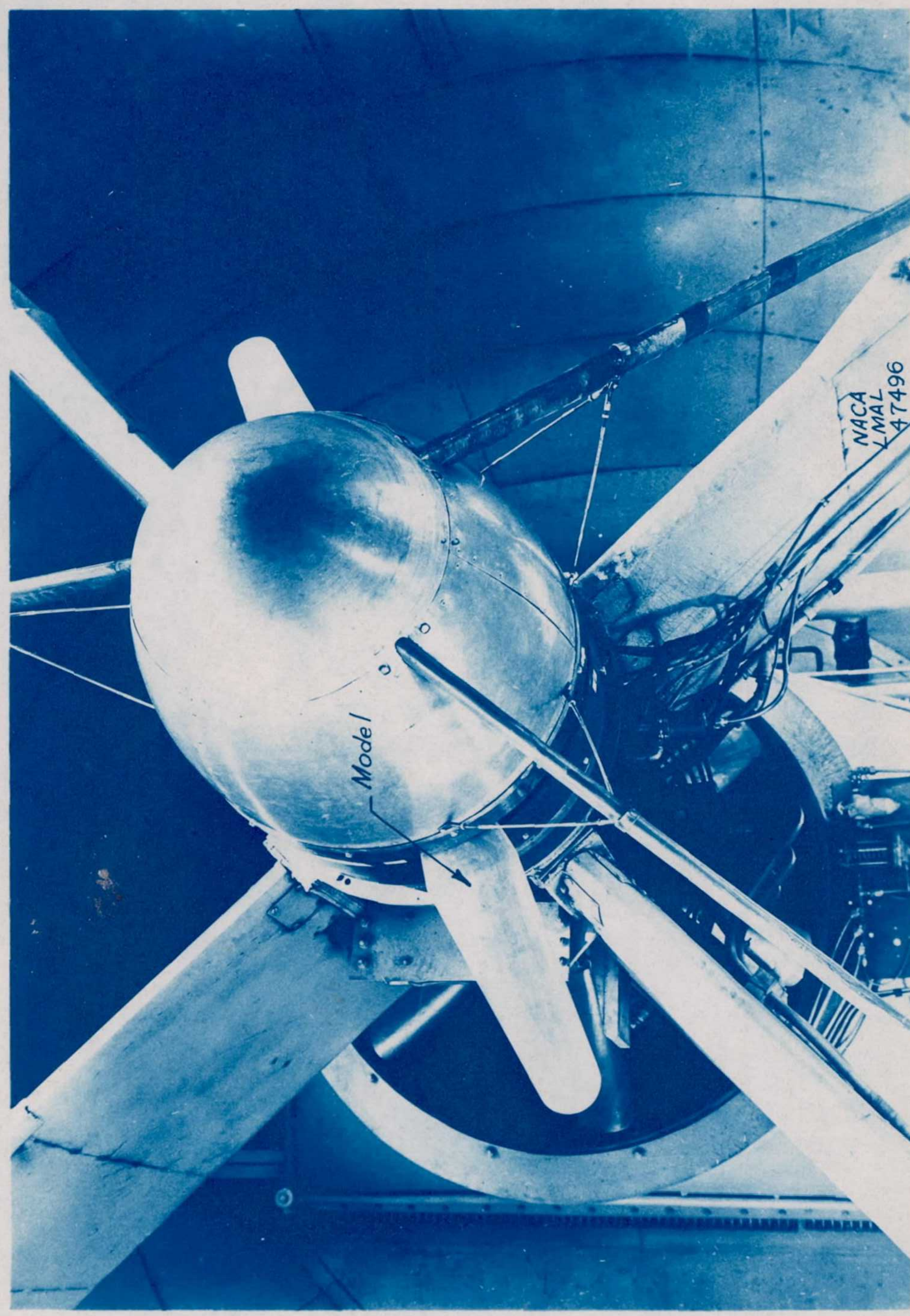

Figure 2.- Interior of the supersonic sphere showing the test-model installation.

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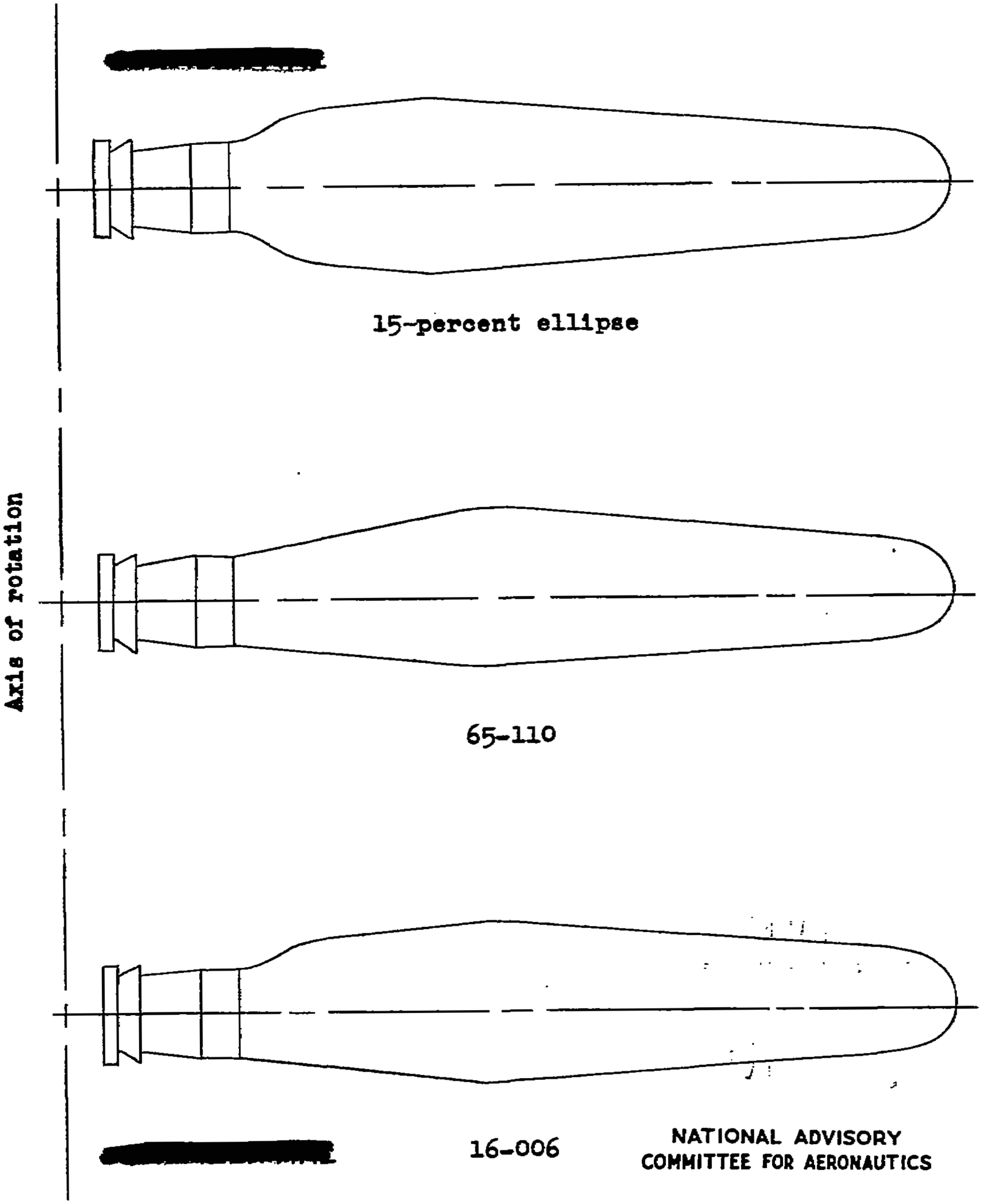

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Figure 3.- Plan form of two-dimensional test models.

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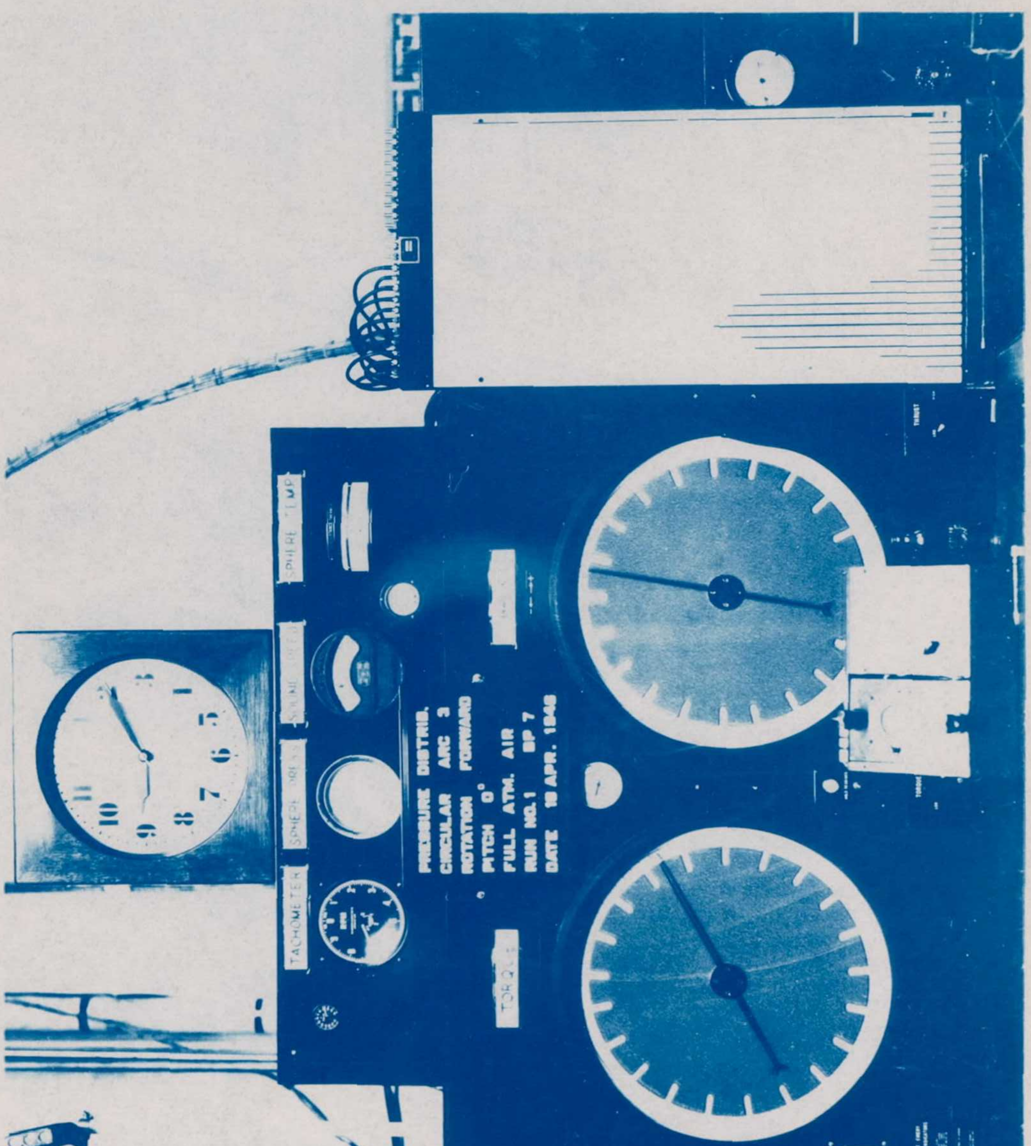

Figure 4.- Supersonic-sphere test panel in operation.

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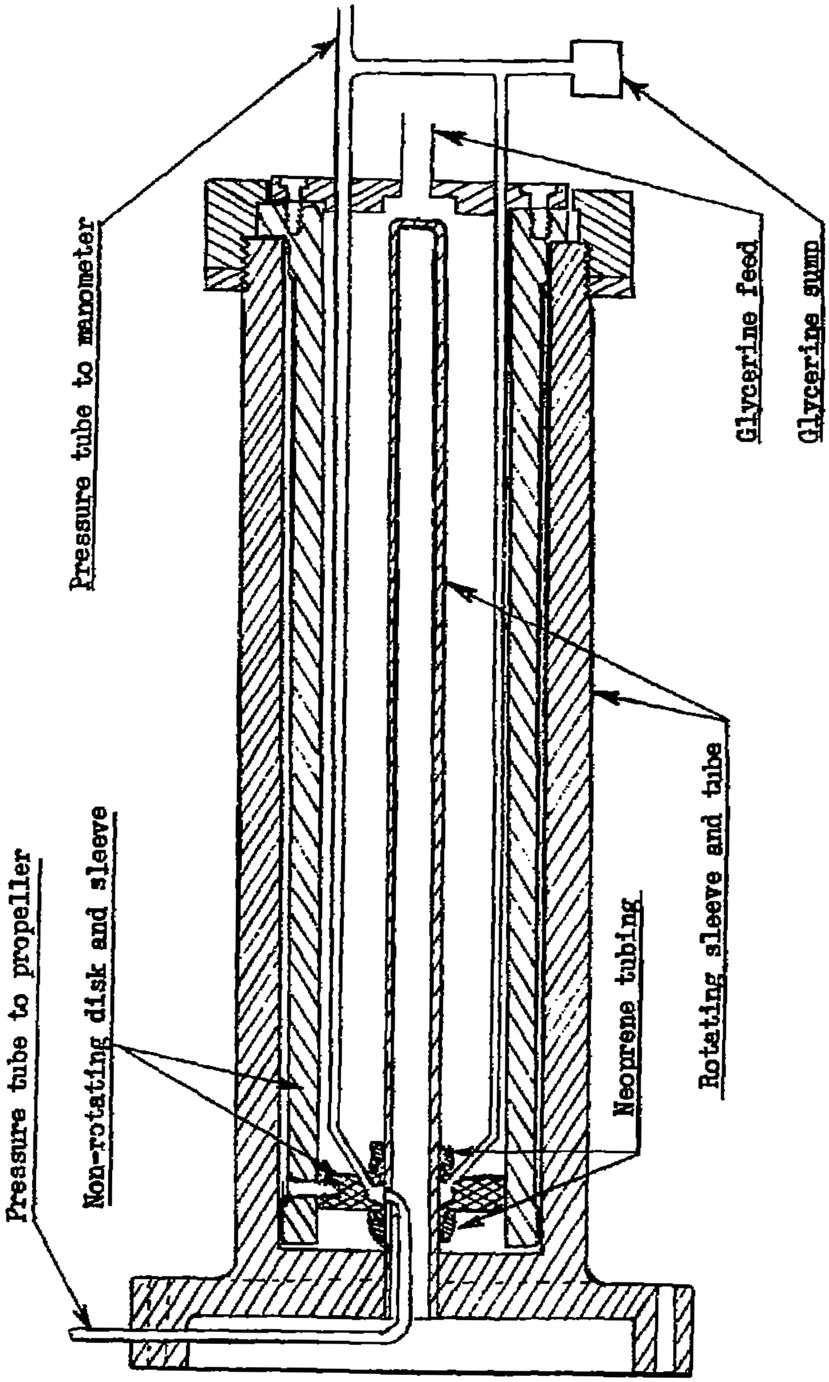

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Figure 5. Cross-section view of pressure transmitter. Only one pressure tube is shown.

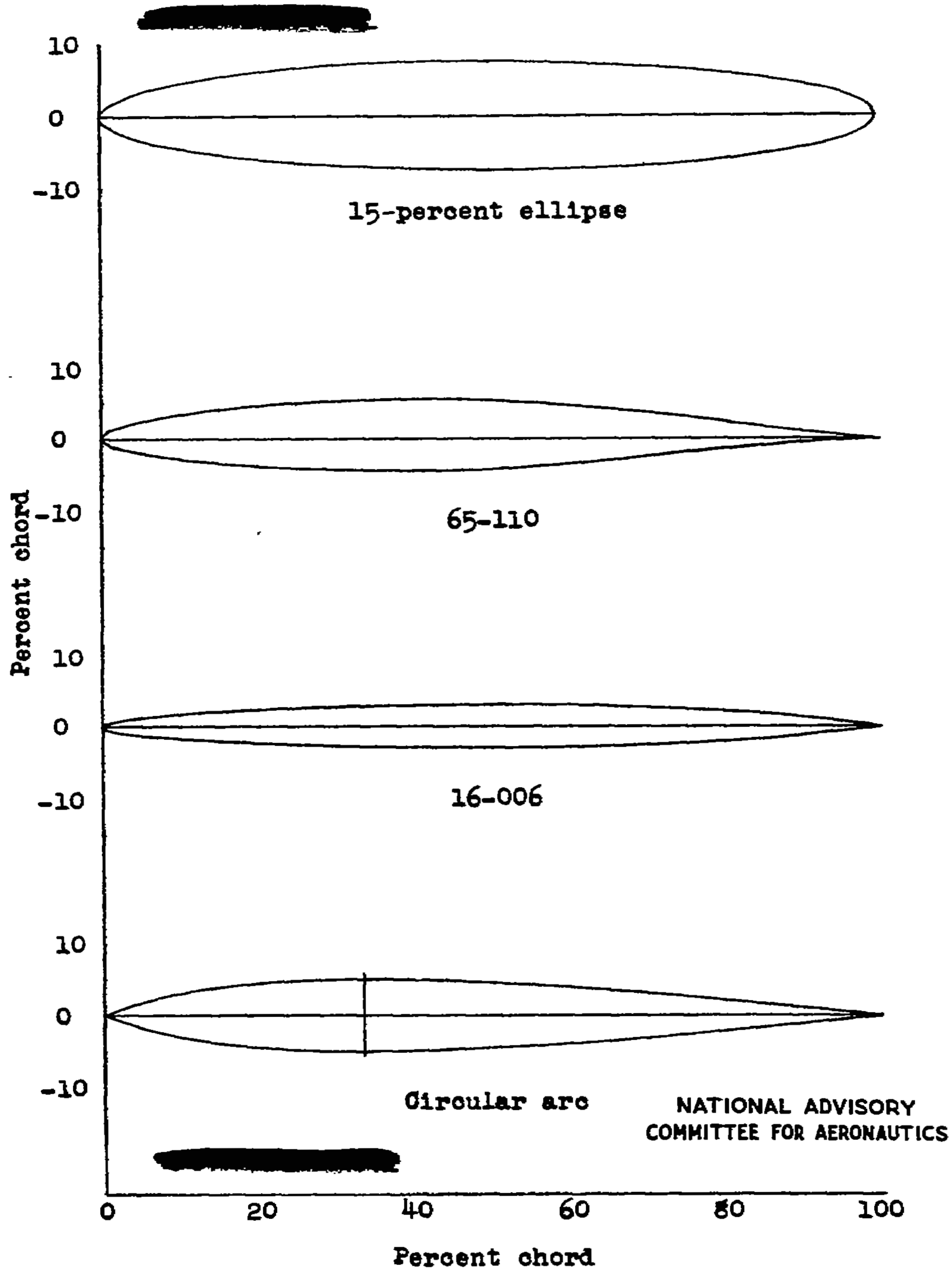

Figure 6.- Airfoil sections of models tested.

[redacted]

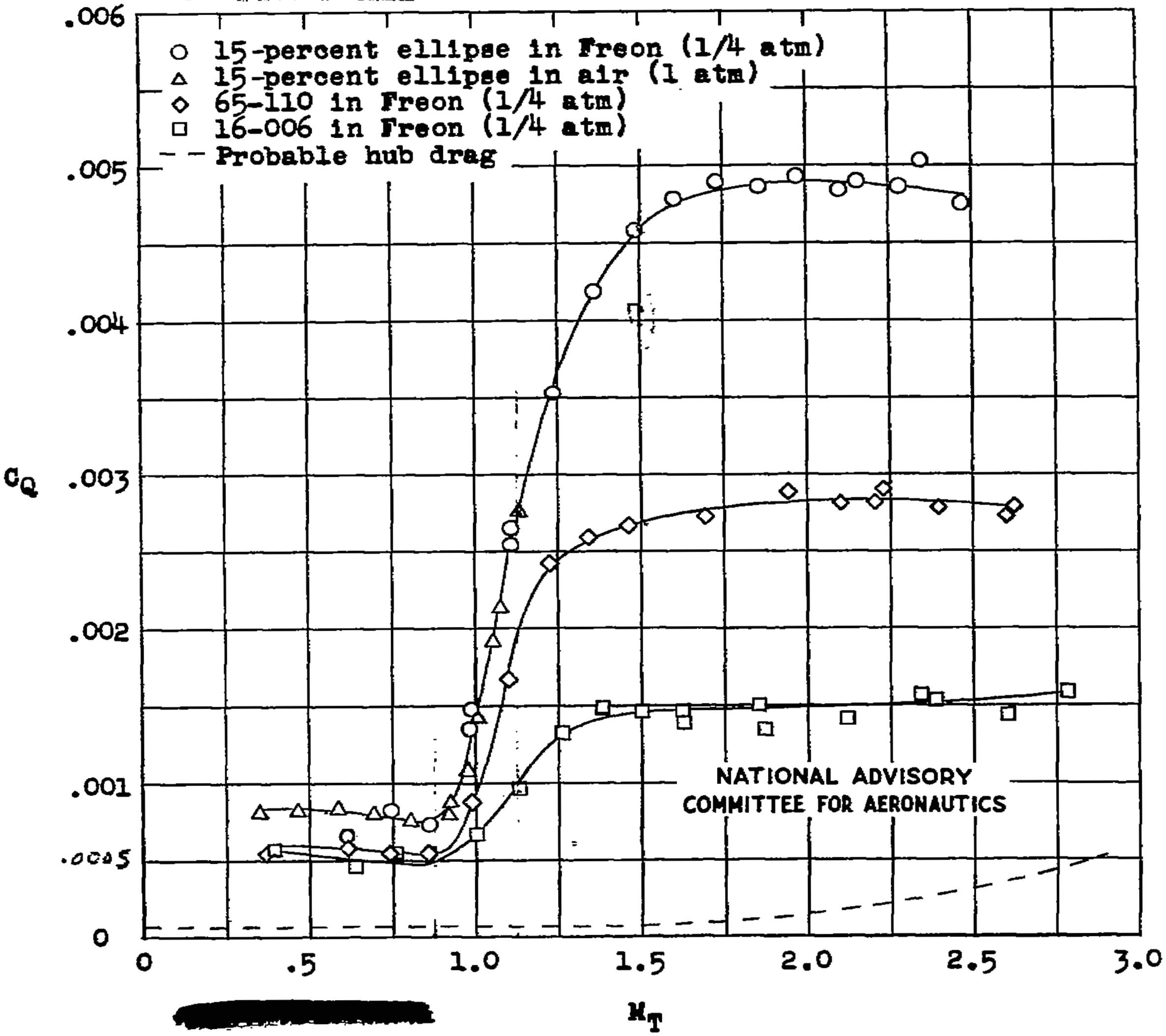

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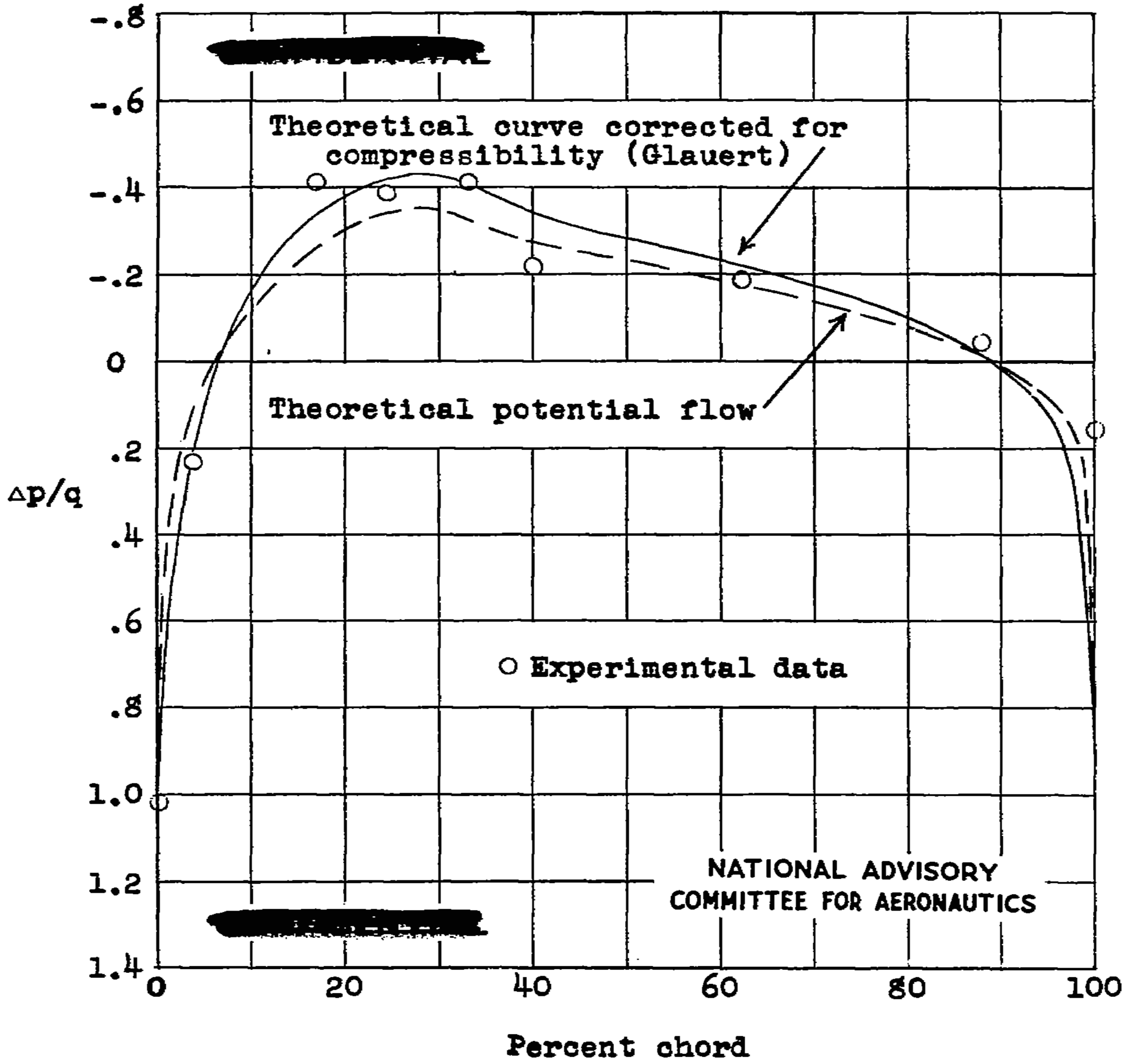
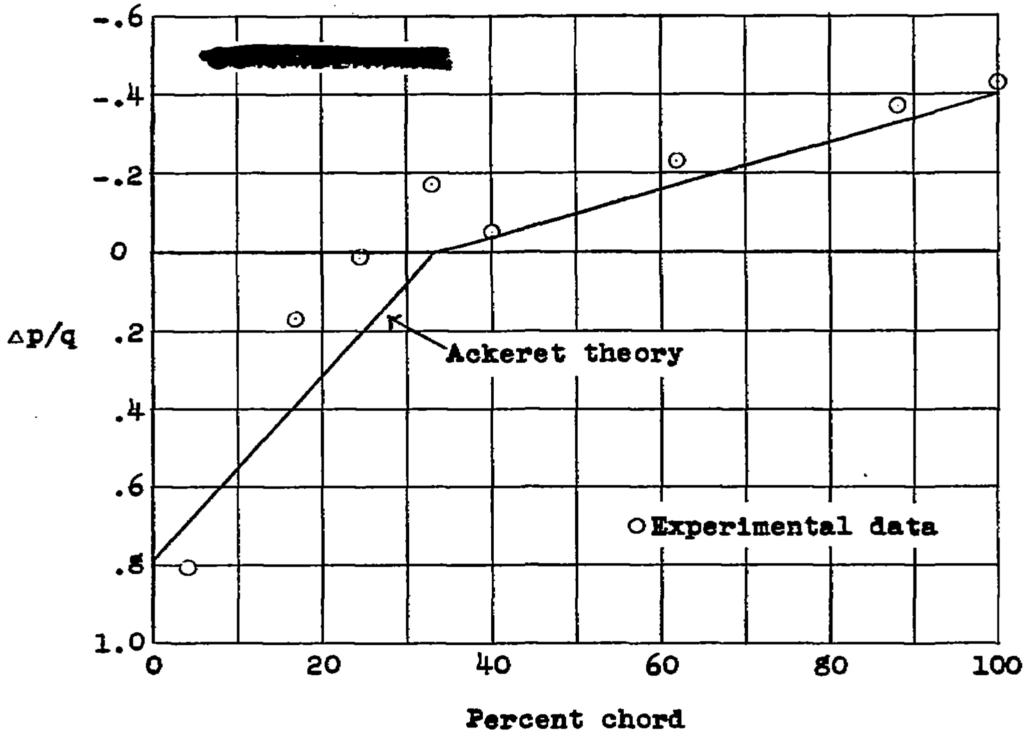
Figure 7.- Effect of Mach number on torque.

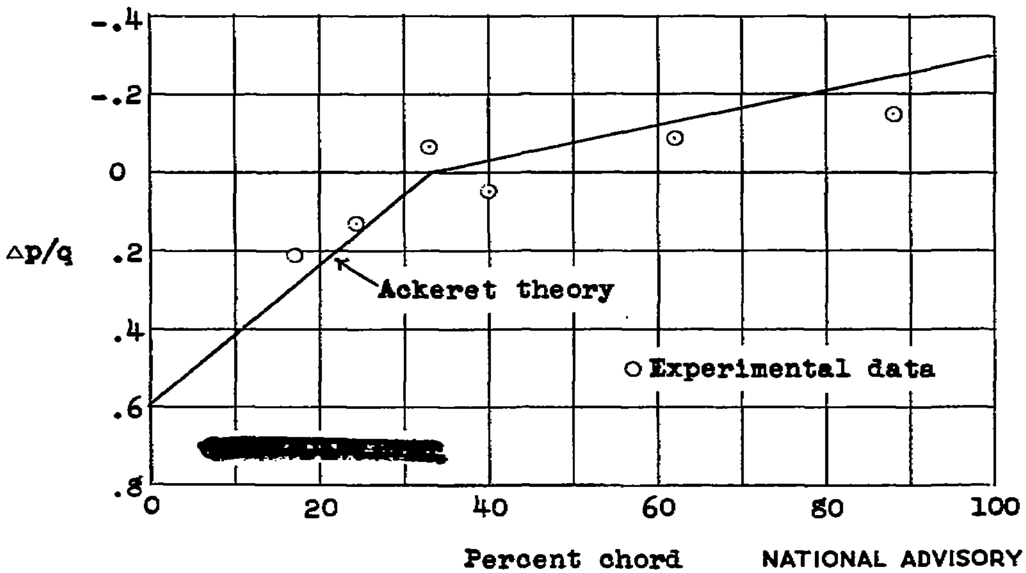


(a) $M = 0.69$

Figure 8.- Pressure distribution on a circular-arc airfoil section.



(b) M = 1.26



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(c) M = 1.42

Figure 8.- Concluded.